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White Paper:
2002 Arizona Reference Case Emissions Inventory for Black Carbon and Organic Material

The Center for Climate Strategies

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This White Paper summarizes the methods, data sources, and results of an estimate of 2002 emissions for black carbon (BC) and organic material (OM) in Arizona. To develop this inventory, we relied on several different data sources. Where possible and within the time-frame available, we used emissions data from the Western Regional Air Partnership (WRAP) to achieve consistency with the regional haze inventory developed for the western States. Data were taken from the following sources:

- Particulate matter (PM) speciation data from EPA's SPECIATE database: these data include aerosol fractions of elemental carbon (aka black carbon) and primary organic aerosols (POA; aka organic material or OM). Our starting point was the speciation data currently being used for regional haze modeling by the Carolina Environmental Program (Vukovich, 2004). Most of these data come from EPA's current SPECIATE3.2 database. We augmented these data with new profiles developed under our ongoing EPA project to update SPECIATE. Note that these new profiles have not yet been released by EPA.

- WRAP's Emissions Data Management System (EDMS): we obtained emissions data for Arizona directly from EDMS for all sources, except wildfires and prescribed burns. We used the particulate matter (PM) emission estimates for AZ from EDMS as one of the primary starting points in this analysis. According to ADEQ, these data represent the best available emissions data compiled for the State. Note that although EDMS was designed to house BC and organic carbon[1] (OC) emission estimates and that WRAP has developed BC and OC estimates for some source sectors, no BC/OC estimates are currently available for AZ in EDMS.

  For the mobile source sector, WRAP developed BC and OC estimates (Environ et al, 2004); however, EDMS indicates that the AZ mobile source data are from EPA's 2002 National Emissions Inventory (NEI). This means that nonroad and onroad Maricopa County data are included, as well as onroad Pima County data (for criteria pollutants). For the rest of the State, EPA populated the data using the National Mobile Inventory Model (NMIM). NMIM uses top-down methods and data sources and the EPA models MOBILE6 and NONROAD 2004 to estimate emissions.

  We reviewed the documentation on how the WRAP mobile source inventory was speciated to derive BC and OC. In most cases, the speciation profiles we used are comparable to those used in the WRAP work as shown below. There are fairly significant differences shown for brake and tire wear. The WRAP fractions for tire wear are based on the original SPECIATE PM profile (circa 1988). Our profile is based on recent data from CARB that will be contained in the latest SPECIATE version. This profile is supported by a study of car tires

[1] Note that OC is a measurement of carbon mass only for the organic material. Other functional groups associated with OM contain atoms of oxygen, nitrogen, hydrogen, and other compounds. Jacobson (2002) used a factor of 1.3 to convert between OC and OM. This compares to a factor of 1.2 used by EPA for its POA estimates (PES, 2003). For this analysis, we assumed POA is equivalent to OM as defined by Jacobson.

showing that carbon black makes up 25-35% of tire rubber (Wik and Dave, 2005). The brake wear profile is also based on new CARB profile data. Instead of using the same BC/OC data for nonroad gasoline exhaust and onroad gasoline exhaust (as was done in the WRAP work), we used an existing SPECIATE profile, which is similar to pre-1991 onroad vehicles. We believe that this profile better represents nonroad gasoline engine emissions (e.g. primarily non-catalyzed and less combustion efficient than newer onroad engines). Secondly, although we do not have speciation data for 2-stroke engines, we expect the OC fractions to be much higher than in onroad gasoline vehicles (thus, the selected profile is a better fit).

Sector	Subsector	WRAP		This Study	
		Weight Fraction[a]			
		BC	OC	BC	OC
Onroad Gasoline	Exhaust	0.239	0.518	0.169	0.597
	Tire Wear	0.609	0.2175	0.22	0.472
	Brake Wear	0.028	0.972	0.0261	0.107
Onroad Diesel	Light Duty Exhaust	0.613	0.303	0.613	0.303
	Heavy Duty Exhaust	0.75	0.189	0.75	0.189
	Tire Wear	0.609	0.2175	0.22	0.472
	Brake Wear	0.028	0.972	0.0261	0.107
Nonroad Gasoline		0.239	0.518	0.0801	0.655
Nonroad Diesel		0.75	0.189	0.7411	0.187

[a] Note that the weight fractions do not add to one, since other aerosol species (not shown) also make up the PM profile – e.g. sulfates, nitrates, metals, etc.

Except for wildfires/prescribed burns, we are not aware of any BC/OC emission estimates from the WRAP (or elsewhere) covering the rest of the stationary source sector (e.g. Pechan developed much of the WRAP's point source inventory data; however we did not provide BC/OC estimates as part of that work).

- For wildfires and prescribed burns: we used State-level particulate matter less than 2.5 microns ($PM_{2.5}$) emissions from the WRAP's draft 2002 inventory (Air Sciences, 2004). We then speciated the BC and POA from the $PM_{2.5}$, using new speciation data from our ongoing SPECIATE update project for EPA. As shown below, these aerosol fractions are nearly identical to those used to develop the WRAP inventory. Note that we could not develop BC/OC estimates directly from the WRAP documentation, since the prescribed burn and wildfire emissions were not broken out separately. For the same reason, we could not use the WRAP BC/OC fractions in this study; however as shown below, the values we used are very similar.

WRAP Draft 2002 Inventory				This Study	
Prescribed Fire – Piled Fuels		Prescribed/Wildfires – Non-Piled Fuels		Prescribed Fires and Wildfires	
Weight Fraction					
BC	OC	BC	OC	BC	OC
0.072	0.54	0.062	0.48	0.075	0.532

Development of BC and OM Mass Emission Estimates

In order to convert the BC/POA estimates into CO_2 equivalents, we first assumed that the POA estimate is a reasonable estimate for OM. The BC and POA (OM) mass emission estimates were derived by multiplying the PM_{10} emission estimates by the appropriate aerosol fraction. After some additional consideration of this approach, we decided that, for certain sources, particulate matter less than 2.5 microns ($PM_{2.5}$) emission estimates would be a better starting point for BC and OM emissions. The source categories where $PM_{2.5}$ estimates were favored over PM_{10} estimates are those associated with fugitive dust emissions. These categories include agricultural tilling, paved and unpaved road dust, and construction activities. These categories tend to have a large amount of coarse mass (particles with mass between PM_{10} and $PM_{2.5}$). Much of this coarse mass is not transported far from the source.

After estimating both BC and OM emissions for each source category, we summed these two aerosol species into a BC+OM estimate. We then collapsed the inventory down to the sector level to be consistent with the gaseous portion of AZ's greenhouse gas (GHG) inventory. The mass emission results are shown in Table 1 below.

Development of CO_{2e} for BC+OM Emissions

We used similar methods to those applied in the northeast for converting BC mass emissions to CO_2 equivalents (ENE, 2004). These methods are based on the modeling of Jacobson (2002) and his updates to this work (Jacobson, 2005a). Jacobson (2005) estimated a range of 90:1 to 190:1 for the climate response effects of BC+OM emissions as compared to CO_2 carbon emissions (depending on either a 30-year or 95-year atmospheric lifetime for CO_2). It is important to note that the BC+OM emissions used by Jacobson were based on a 2:1 ratio of OM:BC (his work in these papers focused on fossil fuel BC+OM).

For Maine and Connecticut, ENE (2004) applied climate response factors from the earlier Jacobson work (220 and 500) to the estimated BC mass to estimate the range of CO_{2e} associated with BC emissions. Note that the analysis in the northeast was limited to BC emissions from onroad diesel exhaust. An important oversight from this work is that the climate response factors developed by Jacobson (2002, 2005a) are on the basis of CO_2 carbon (not CO_2). Therefore, in order to express the BC emissions as CO_{2e}, the climate response factors should have been adjusted upward by a factor of 3.67 to account for the molecular weight of CO_2 to carbon (44/12).

For this inventory, we started with the 90 and 190 climate response factors adjusted to 330 and 697 to obtain a low and high estimate of CO_{2e} for each sector. An example calculation of the CO_{2e} emissions for 10 tons of PM_{10} from onroad diesel exhaust follows:

BC mass = (10 tons PM_{10}) x (0.613 ton EC/ton PM_{10}) = 6.13 short tons BC

Low estimate CO_{2e} = (6.13 tons BC) (330 tons CO_{2e}/ton BC+OM) (3 tons BC+OM/ton BC) (0.907 metric ton/ton) = 5,504 metric tons CO_{2e}

High estimate CO_{2e} = (6.13 tons BC) (697 tons CO_{2e}/ton BC+OM) (3 tons BC+OM/ton BC) (0.907 metric ton/ton) = 11,626 metric tons CO_{2e}

The factor 3 tons BC+OM/ton BC comes directly from the modeling assumptions used by Jacobson (2002, 2005a; i.e. 2 tons of OM/ton of BC).

For source categories that had an OM:BC mass emission ratio >4.0, we zeroed out these emission estimates from the CO_{2e} estimates. The reason for this is that the net heating effects of OM are not currently well understood. Therefore, for source categories where the PM is dominated by OM (e.g. biomass burning), the net climate response associated with these emissions is highly uncertain. Further, OM:BC ratios of 4 or more are well beyond the 2:1 ratio used by Jacobson in his work.

Results, Conclusions and Next Steps

We estimate that BC mass emissions in AZ total 12,370 tons in 2002 (see Table 1). The CO_{2e} emissions range from about 2.8 to 6.0 million metric tons. These estimates are approximately 3 to 6 percent of the entire CO_{2e} estimated for the gaseous GHG inventory. Wildfires and prescribed burns contributed nearly 68% of the BC mass emissions; however they were removed from the CO_{2e} estimates due to the high OM to BC ratio (about 7:1). Emissions for residential wood combustion and open burning, two more important biomass combustion sectors, were also left out of the CO_2e estimates for the same reason.

By far, the highest contributions to CO_2e are from the onroad diesel sector at 59% (this includes exhaust, plus brake and tired wear). Nonroad diesel engines contribute 18% of the CO_{2e} emissions. Construction diesel engines contributed nearly 60% of the CO_2e for the nonroad diesel engines sector. The "nonroad other" sector contributes about another 11% of the CO_2e. This sector is dominated by railroad engines. Onroad gasoline vehicles contribute another 3%, however these emissions are strictly related to tire wear (the OM:BC ratios for exhaust and brake wear are both >4). Coal-fired electricity generating units (EGUs) contribute 6% of the CO_{2e}.

If directed to do so by the AZ Climate Change Advisory Group, our next steps will be to develop projection year estimates. We suggest focusing on just the primary CO_2e contributors (e.g. onroad diesel and the nonroad diesel sectors. Forecast inventories from the Western Regional Air Partnership (WRAP) process could be used and are recommended in order to maintain consistency with the regional haze program. To represent 2010 conditions, the WRAP 2008 forecast year would provide the best estimates. For 2020, the WRAP 2018 forecast is the best surrogate.

While the state of science in aerosol climate forcing is still developing, there is a good body of evidence supporting the net warming impacts of black carbon. Aerosols have a *direct* radiative forcing because they scatter and absorb solar and infrared radiation in the atmosphere. Aerosols also alter the formation and precipitation efficiency of liquid water, ice and mixed-phase clouds, thereby causing an *indirect* radiative forcing associated with these changes in cloud properties (IPCC, 2001). There are also a number of other indirect radiative effects that have been modeled (e.g. Jacobson, 2002).

The quantification of aerosol radiative forcing is more complex than the quantification of radiative forcing by greenhouse gases because the direct and indirect radiative forcing, and the fact that aerosol mass and particle number concentrations are highly variable in space and time. This variability is largely due to the much shorter atmospheric lifetime of aerosols compared with the important greenhouse gases. Spatially and temporally resolved information on the atmospheric burden and radiative properties of aerosols is needed to estimate radiative forcing.

The quantification of indirect radiative forcing by aerosols is especially difficult. In addition to the variability in aerosol concentrations, some quite complicated aerosol influences on cloud processes must be accurately modeled. For example, the warm (liquid water) cloud indirect forcing may be divided into two components. The first indirect forcing is associated with the change in droplet concentration caused by increases in aerosol cloud condensation nuclei. The second indirect forcing is associated with the change in precipitation efficiency that results from a change in droplet number concentration. Quantification of the latter forcing necessitates understanding of a change in cloud liquid-water content and cloud amount. In addition to warm clouds, ice clouds may also be affected by aerosols.

To put the radiative forcing potential of BC in context with CO_2, the Intergovernmental Panel on Climate Change estimated the radiative forcing for a doubling of the earth's CO_2 concentration to be 3.7 watts per square meter (W/m^2). For BC, various estimates of current radiative forcing have ranged from 0.16 to 0.42 W/m^2 (IPCC, 2001). These BC estimates are for direct radiative effects only. There is a higher level of uncertainty associated with the direct radiative forcing estimates of BC compared to those of CO_2 and other GHGs. There are even higher uncertainties associated with the assessment of the indirect radiative forcing of aerosols.

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Table 1. BC+OM Emissions Summary

Sector	Subsector	Mass Emissions					CO_{2e}	
		BC	POA	BC	POA	BC + OM	Low	High
		Short Tons		Metric Tons			Metric Tons	
Electric Generating Units (EGUs)	Coal	193	275	175	250	425	173,028	365,456
	Oil	1.1	0.4	1.0	0.33	1.3	994	2,100
	Gas[a]	0	94	0	86	86	0	0
Non-EGU Fuel Combustion	Coal	5.7	8.2	5.2	7.5	13	5,161	10,900
(Residential,Commercial, and Industrial)	Oil	22	11	20	9.5	29	19,691	41,589
	Gas	0.03	241	0.03	218	218	0	0
	Other[b]	237	1,161	215	1,054	1,269	1,985	4,193
Onroad Gasoline (Exhaust, Brake Wear, & Tire Wear)		192	737	174	669	843	82,966[c]	175,235[c]
Onroad Diesel (Exhaust, Brake Wear, & Tire Wear)		1,864	728	1,692	661	2,353	1,671,922	3,531,302
Aircraft[d]		50	28	45	25	70	44,589	94,177
Other Energy Use	Nonroad Gasoline	52	560	47	508	555	0	0
	Nonroad Diesel	579	193	526	175	701	520,169	1,098,660
	Nonroad Other[e]	338	106	307	96	403	303,511	641,160
	Other Combustion[f]	8.7	72	7.9	65	73	237	500
Industrial Processes[g]		42	606	38	550	588	326	690
Agriculture[h]		27	1,362	25	1,236	1,261	0	0
Waste Management	Landfills	0.12	7.3	0.11	6.6	7	0	0
	Incineration[i]	5.3	9.8	4.8	8.9	14	4,741	10,015
	Open Burning[j]	260	3,039	236.28	2,758.88	2,995	0	0
Wildfires/Prescribed Burns[k]		8,400	71,501	7,626	64,909	72,534	0	0
Miscellaneous[l]		94	1,446	85	1,312	1,398	86	182
	Totals	**12,370**	**82,183**	**11,230**	**74,606**	**85,835**	**2,829,406**	**5,976,157**

NOTE: CO_2e is zeroed out for sources with OM:BC ratio >4.0 (see text).

[a] The SPECIATE3.2 PM profile showed zero for PEC (BC). A review of other in-house data showed that BC is present in PM emissions from natural gas combustion at a OM:BC ratio of around 1:1. This ratio was used to calculate BC+OM and the associated CO_{2e} emissions.

[b] Most of these emissions are from residential wood combustion.

[c] The CO_2e estimates are associated with tire wear only, since the exhaust and brake wear components have OM:BC ratios >4:1.

[d] Note for aircraft, criteria pollutant emissions are only estimated for the boundary (mixing) layer (i.e., mainly landing and take-off cycle emissions). Therefore, these estimates do not include emissions occurring above the mixing layer but within AZ airspace.

[e] Nearly all emissions are from the railroad source categories.

[f] About 60% of emissions are from vehicle fires. Other contributors include structure fires and aircraft/rocket engine firing and testing.

[g] In this summary, construction is included in the Industrial Processes sector. Construction source categories (industrial/commercial/institutional, residential, road, and other) are the major contributors (96%) of the Industrial Processes emissions.

[h] The Agriculture sector includes food industries. 80% of the BC emissions come from agricultural tilling. Agricultural tilling and commercial cooking each contribute about 43% of the POA emissions.

[i] About 97% of BC and POA emissions come from commercial/institutional incineration.

[j] Open burning of land clearing debris contributes about 68% of BC/POA emissions. Other contributors include open burning of yard waste and household waste.

[k] Wildfire/Prescribed burn emissions were excluded from the CO_2e estimates due to the much higher OM to BC ratio (about 7:1).

[l] Paved and unpaved road dust are significant contributors to the EC and OC emissions.